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# Acoustically Forced Coaxial Hydrogen / Liquid Oxygen Jet Flames

## ILASS Americas 28th Annual Conference on Liquid Atomization and Spray Systems
## Dearborn, MI, May 2016

Mario Roa, Dave Forliti, Sierra Lobo, Inc.
Al Badakhshan, ERC Inc.
Doug Talley, AFRL

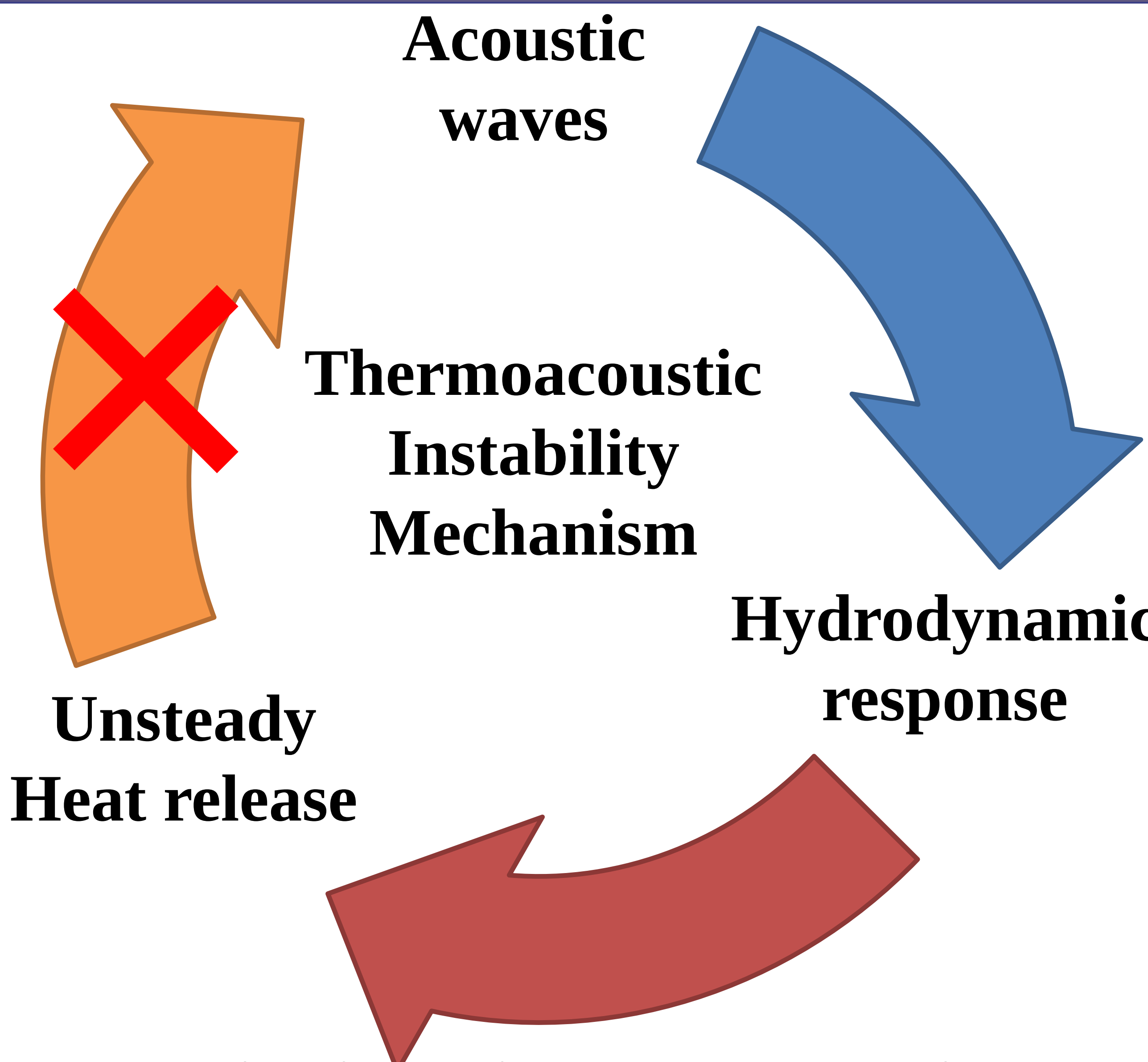
# AF relevant considerations

- **Achieving modern thermodynamic efficiencies requires achieving increasingly higher chamber pressures, sometimes exceeding the critical pressure of the reactants**
  - e.g., liquid rockets, future gas turbines
- **When the combustion systems are for propulsion, limited tankage dictates that on-board propellants be stored in condensed form**
  - e.g., kerosene, liquid oxygen in rockets
- **Combustion systems can no longer be designed to meet modern requirements without considering system dynamics**
- **Combustion dynamics always includes acoustic waves, which in enclosed systems can sometimes reach detrimental amplitudes**
  - e.g., combustion instabilities

# Objectives

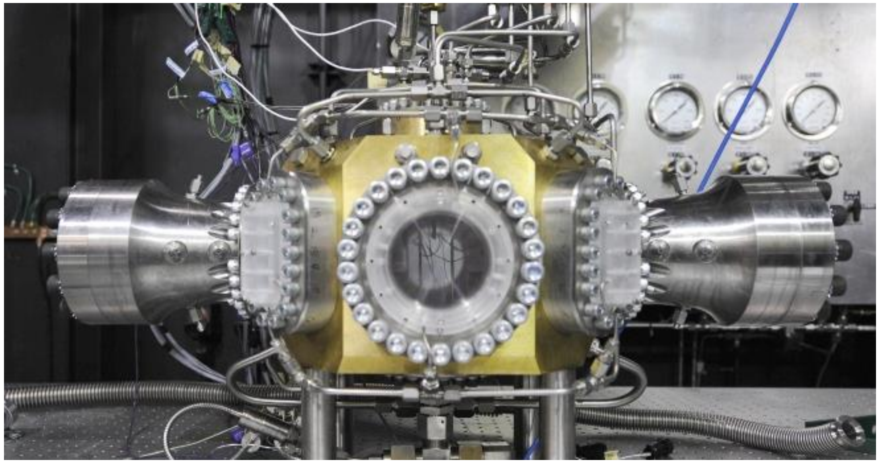
- **Determine the mechanisms governing the dynamics of a high pressure, chemically reacting, multiphase, acoustically driven, shear flow in the form of a coaxial jet flame.**
- **Explore how the presence of chemical reactions affects the response of coaxial jets to acoustic forcing.**
- **Explore inter-element interactions.**

# Approach




Open the loop for better control

# Experimental Facility



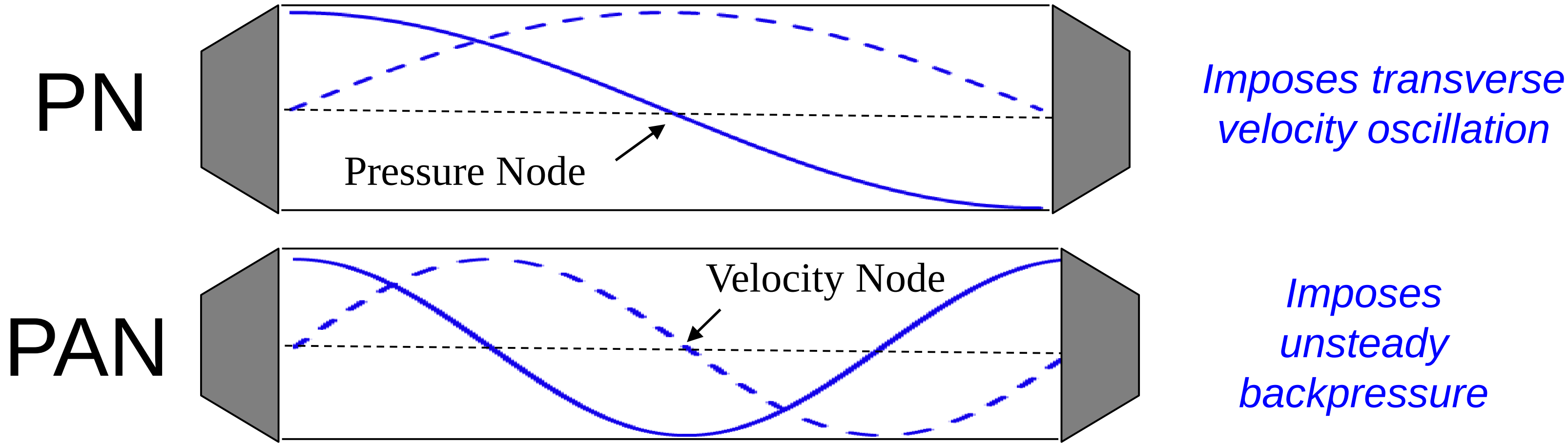
**Features**

- Frequency and amplitude independent of combustion – accurate control of frequency and amp.
- Pressurization independent of combustion – accurate control of pressure.
  - Subcritical and supercritical pressures
- Precise cryocooler – accurate control of temperature to within ±1 K.
- Chamber-within-a-chamber
  - Outer chamber contains pressure – pressure containing elements remain cool
  - Inner chamber contains acoustics and combustion only – allows finer adjustment of inner elements
- High amplitude piezosirens specially designed for high pressure
- On-axis windows for shadowgraph, Schlieren, chemiluminescence, OH* emission
- Off-axis windows for PIV/PLIF
- Fully developed turbulent injector flows – well known boundary conditions
- High-speed pressure transducers

Rayleigh Index fields

# Summary of Forcing Conditions

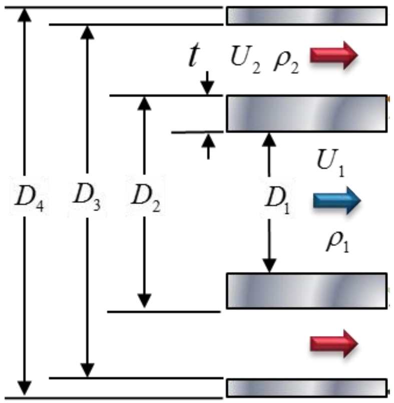
- **Pressure node (PN) and pressure antinode (PAN) at the injector location**

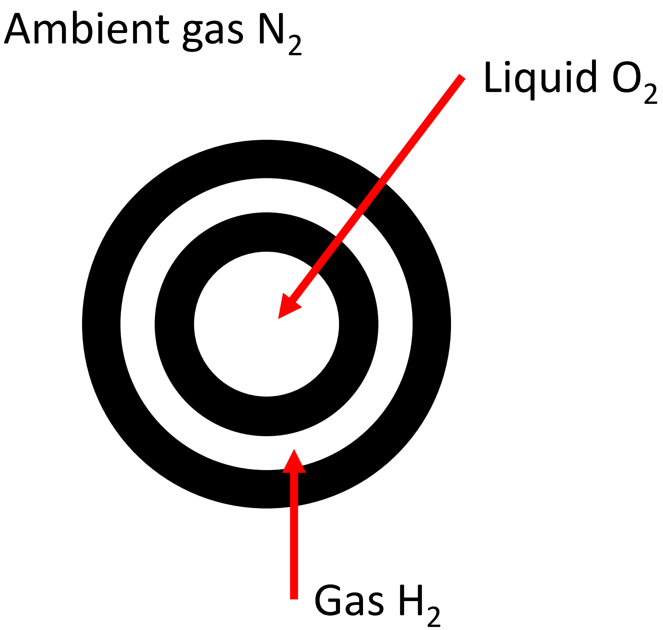



- **Forcing frequency ~ 3000 Hz**
- **Pressure fluctuation amplitudes (peak-to-peak) range up to approximately 9 psi (6 psi reacting)**

# Operating Conditions

- **Cryogenic liquid $O_2$ and gaseous $H_2$ flame**
- **Injector geometry**
  - $D_1$ = 1.4 mm
  - AR = 1.68
  - $t/D_1$ = 0.27
- **J ≈ 2.2**
- **MR ≈ 6-7**
- **$O_2$ inner jet @ 140 K**
- **$H_2$ outer jet @ 250 K**
- **Fully-developed turbulent flow conditions**
- **Chamber pressure 3.4 MPa (500 psi)→ subcritical**

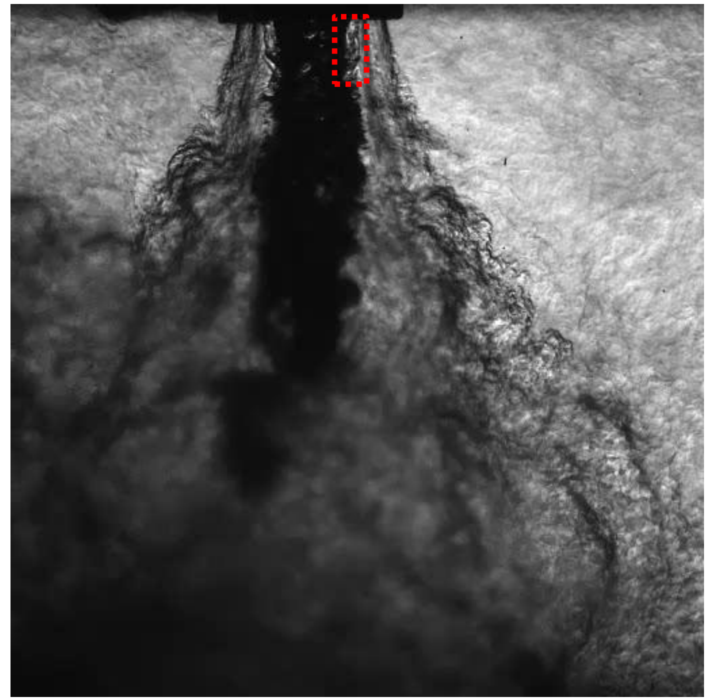


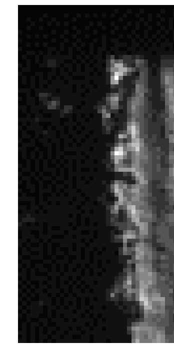



# Unforced Results

Nonreacting

Reacting



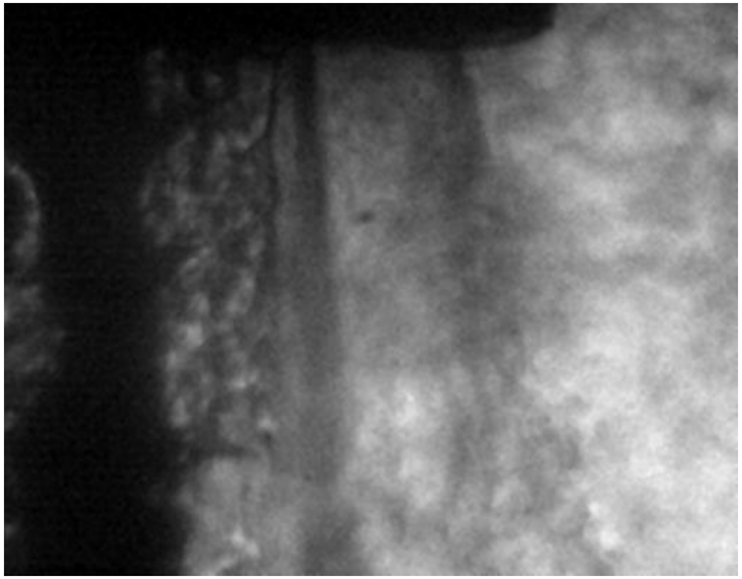


**Differences:**

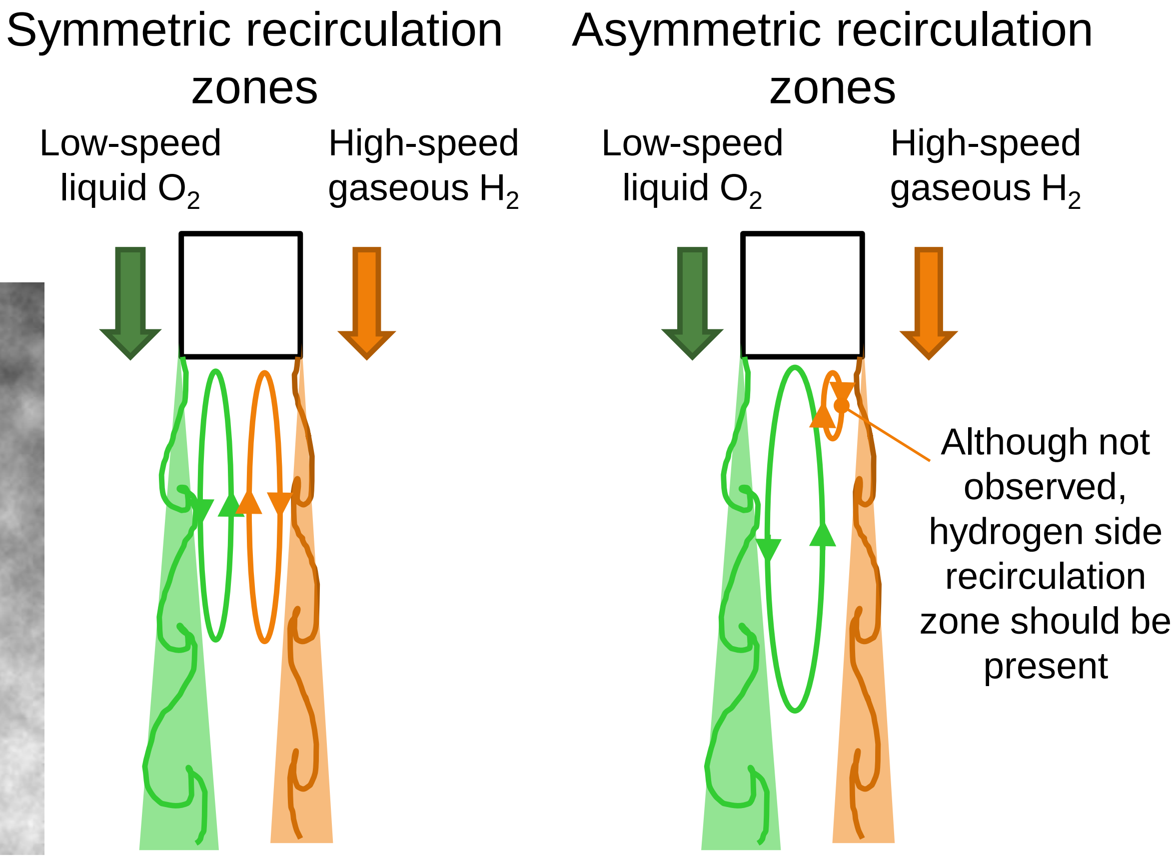
- Flame reduces fine fibrous structure of liquid oxygen surface topology
- Flame increases the characteristic time scales of the liquid structures
- Flame allows optical access to recirculation zone—reverse flow observed

# Recirculation Zone Phenomenon

Combustion case



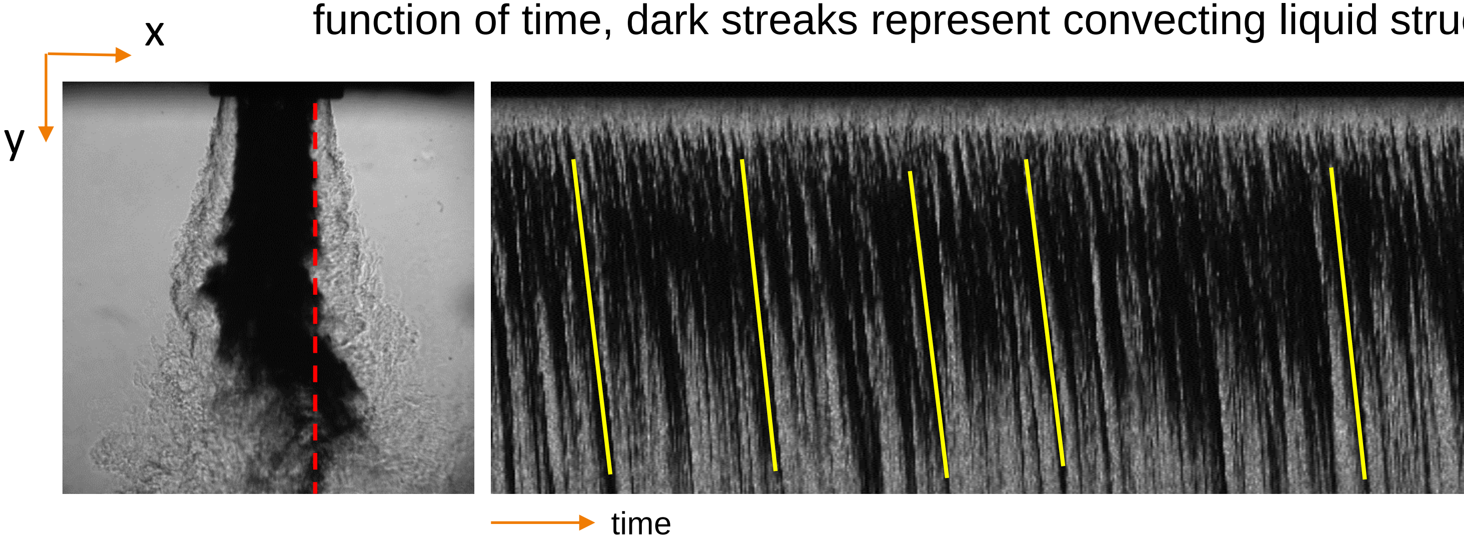
100kHz Framerate



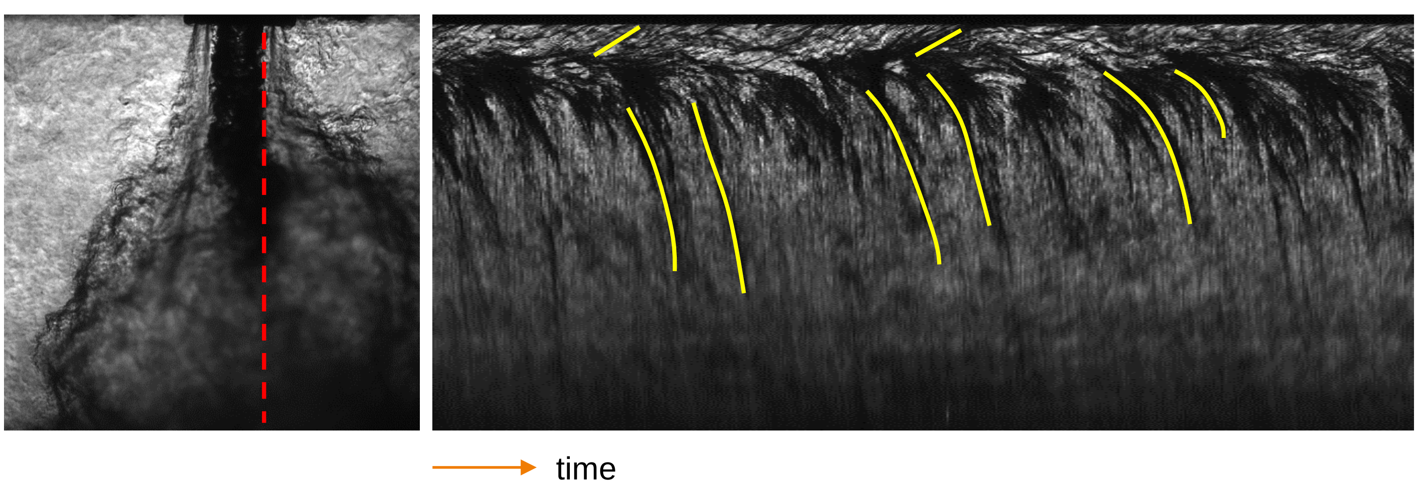

*Results show large oxygen-side recirculation zone that brings liquid $O_2$ structures very close to hydrogen shear layer.*

# Convection Velocities

Extract column of pixels at each time along shear layer edge as a function of time, dark streaks represent convecting liquid structures



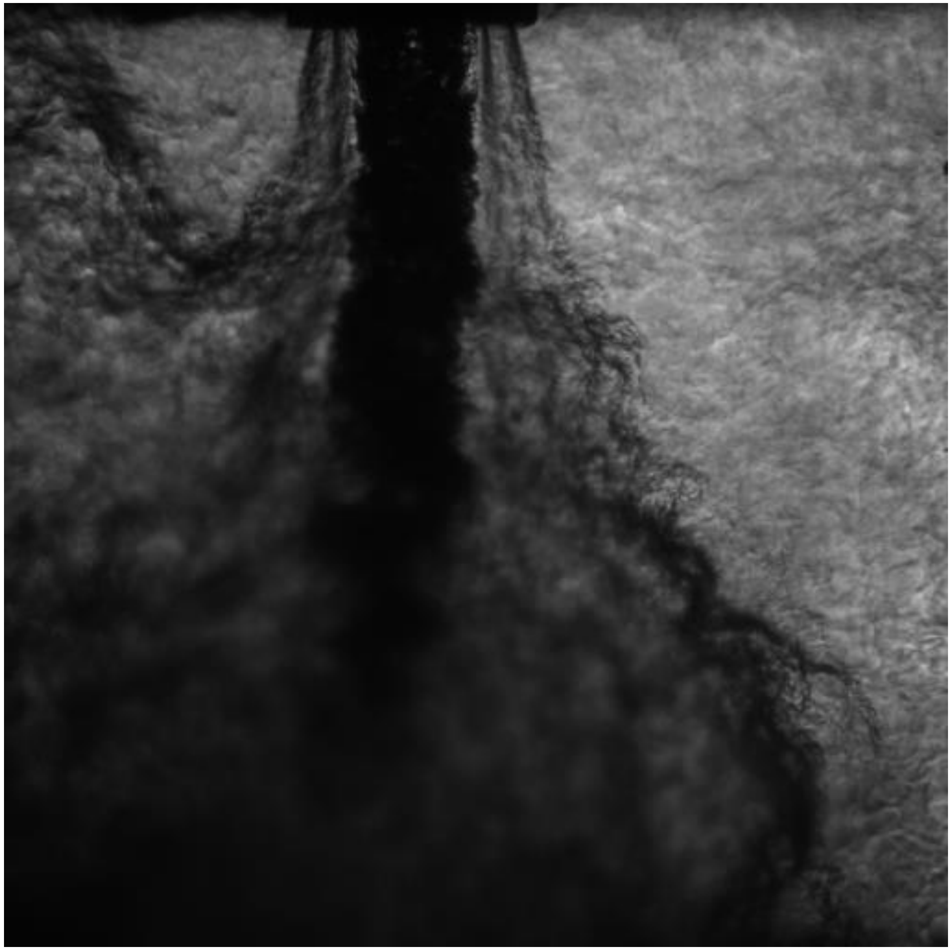

Structures convect at apparent constant velocity

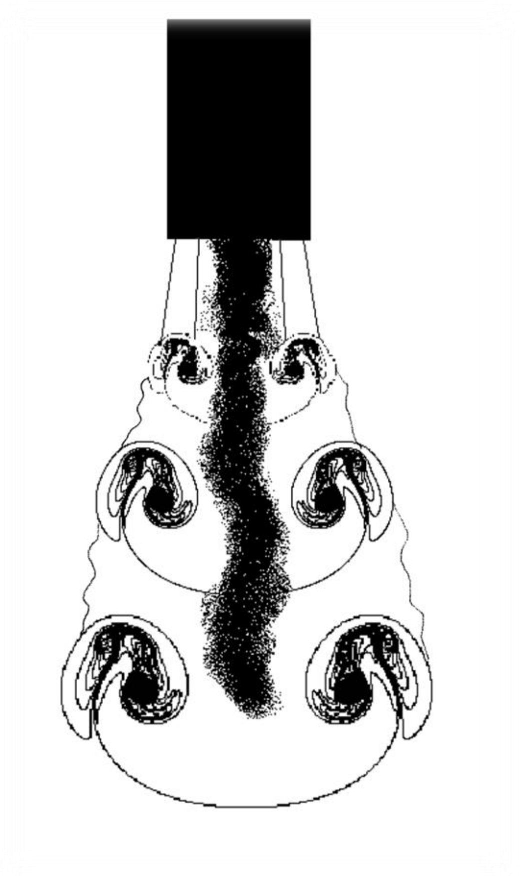



Positive slope streaks represent upstream traveling features

Structures start at slow speed and gradually accelerate with downstream distance

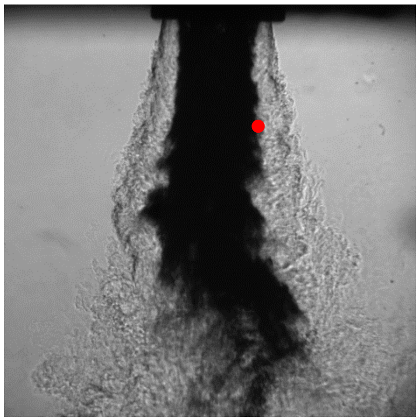
# Downstream combustion structures



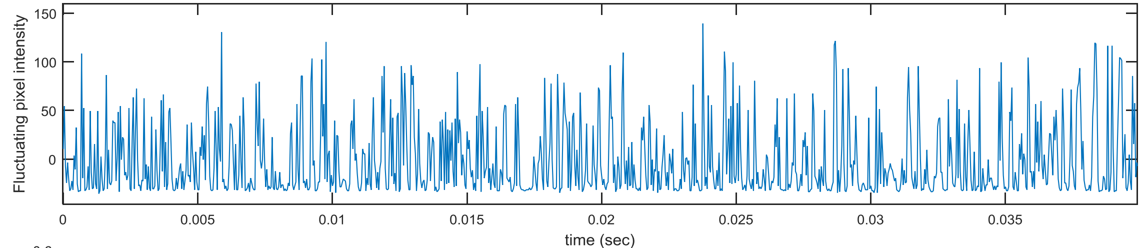


# Near Field Shear Layer Dynamics

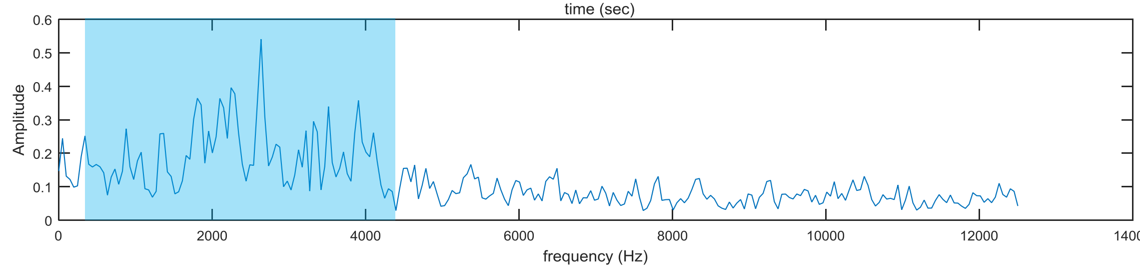
Temporal pixel fluctuations at $x/D_1 = 2$

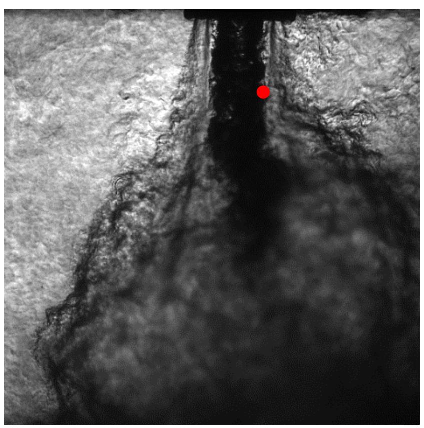


**Time series**

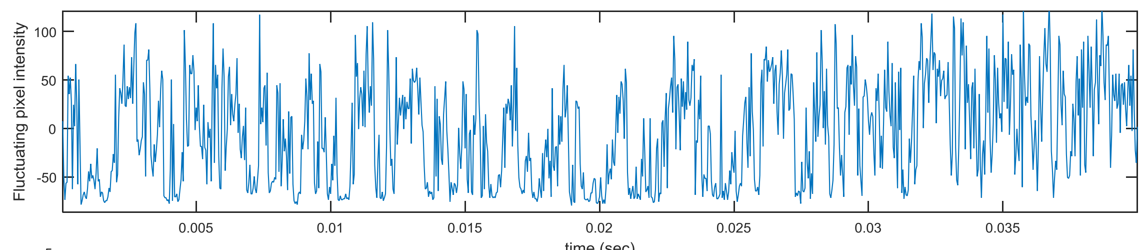



**PSD**

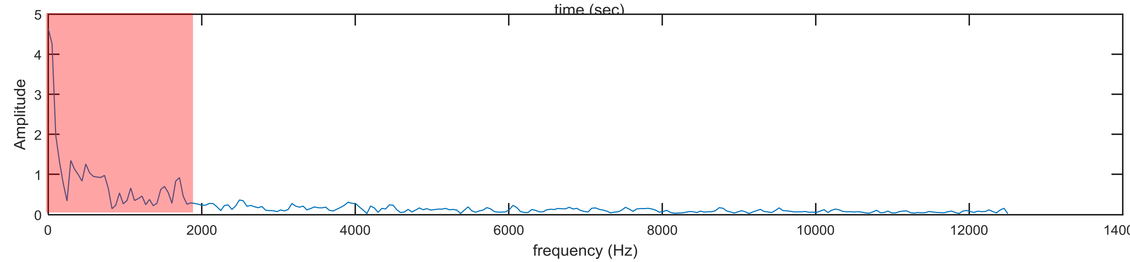


**Time series**




**PSD**




***Shift of spectral content to lower frequencies***

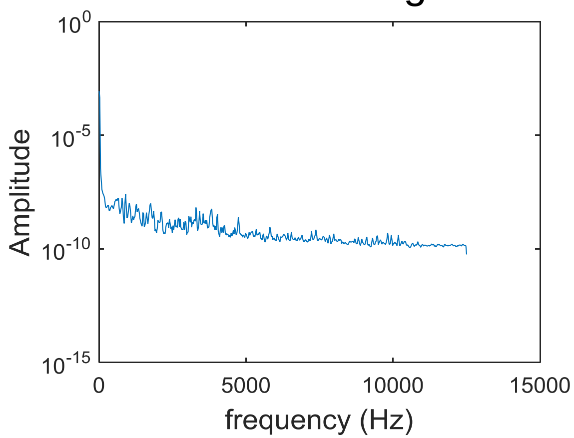
# Linear Stability Considerations

- **Mahalingam et al. (1991) predict a stabilization and shift to lower frequencies for a flame located in a jet shear layer**
- **Hajesfandiari and Forliti (2014) showed a similar trend for planar shear layers**
- **Furi et al. (2002) showed a damping effect of the flame on a shear layer, depending on the relative location of the flame within the vorticity profile**

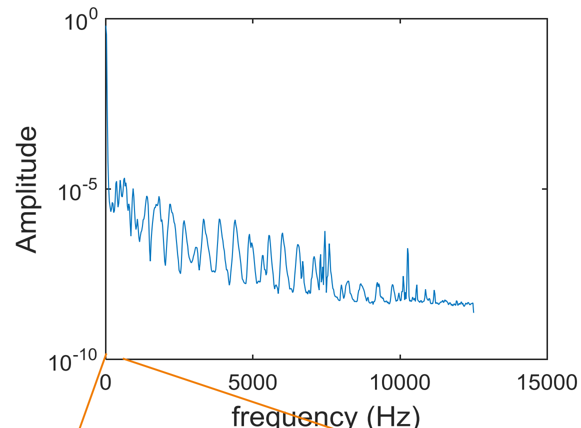
# Chamber Acoustics, no Forcing

## Spectra of chamber pressure fluctuations

Nonreacting

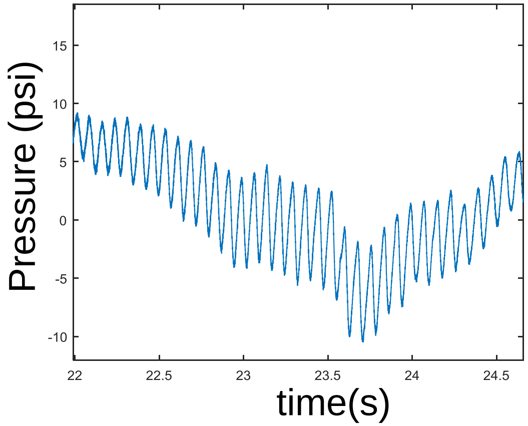


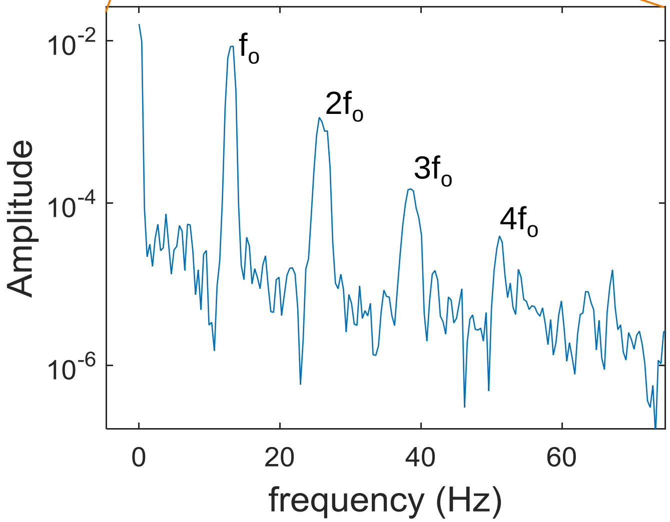

Reacting




Zoom in on low frequency

13 Hz low frequency mode present for combustion. Control of this mode will be the subject of near-term research efforts.



# PAN Acoustic Forcing

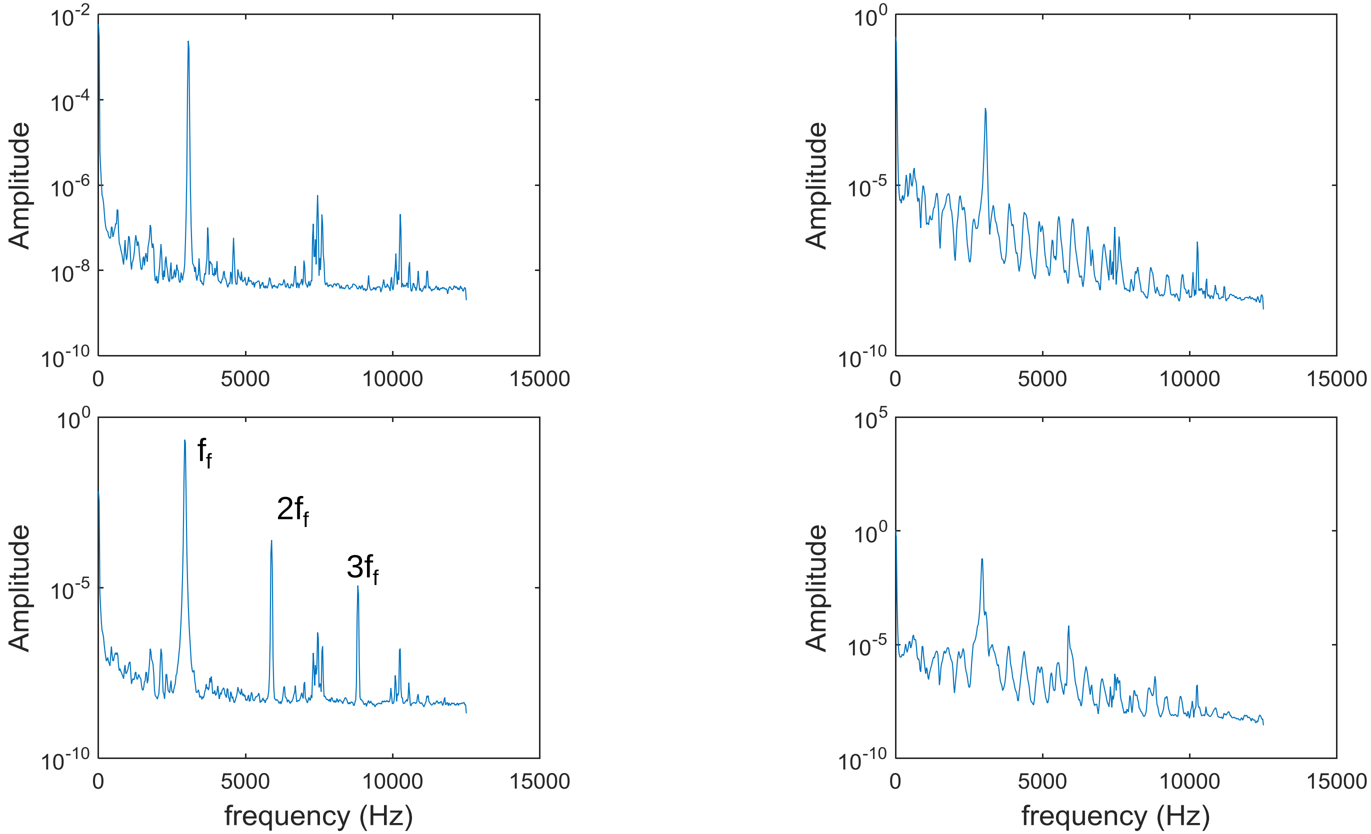
Pressure antinode (PAN), forcing near 3000 Hz

Nonreacting

Reacting

~ 1 PSIA

~ 5 PSIA

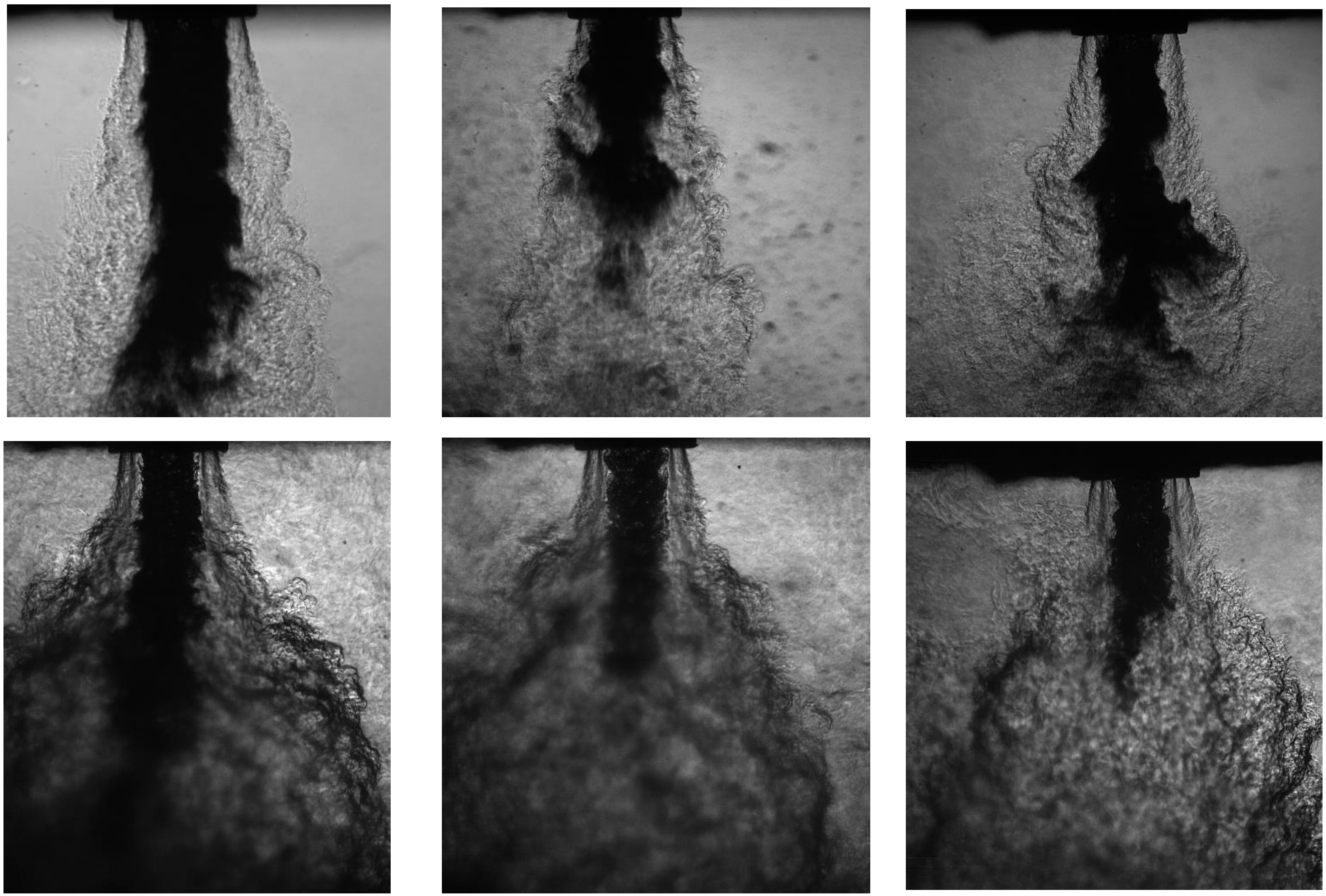


# Acoustic Forcing Behavior

Unforced | PAN Forcing | PN Forcing

Nonreacting

Reacting



No evidence that acoustics affects flame holding

# Dynamic Mode Decomposition

Extract spectrally-pure temporal modes with detailed spatial mode shapes

- Schmid (2010) and Rowley et al. (2009)
- Employ time-averaged amplitude measurement described by Alenius (2014)
- 1000-2000 sampled used

**Amplitude of mode at t = 0**

$$I(x,y,t) = \bar{I}(x,y) + \mathrm{Re}\left( \sum_{i=1}^{n} \tilde{A}_i \exp(\tilde{\lambda}_i t) \tilde{D}_i(x,y) \right)$$

**Time average image subtracted from data**

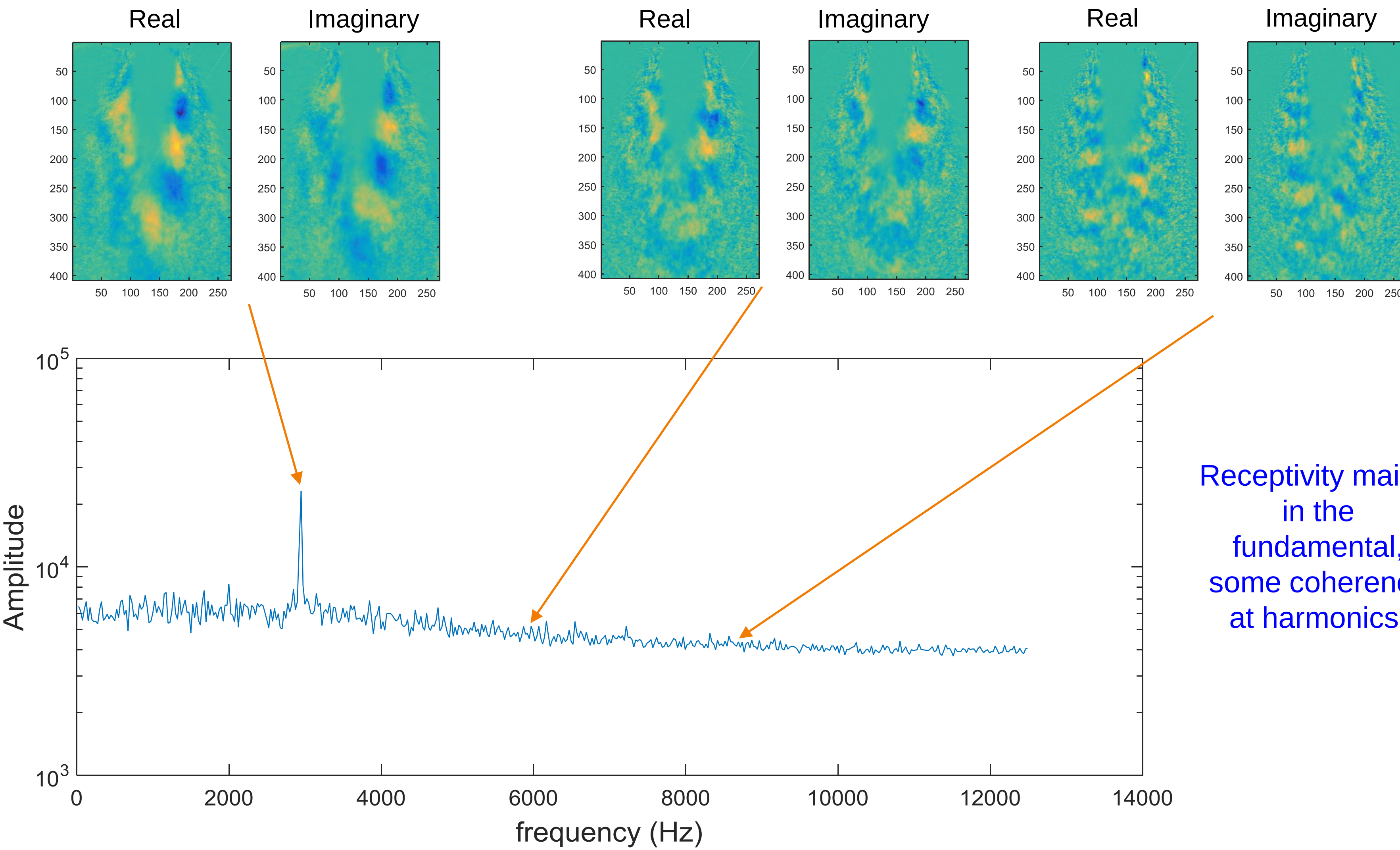
**Accounts for growth of mode in time as well as temporal frequency**

**Complex spatial mode shape**

**Properties of DMD**

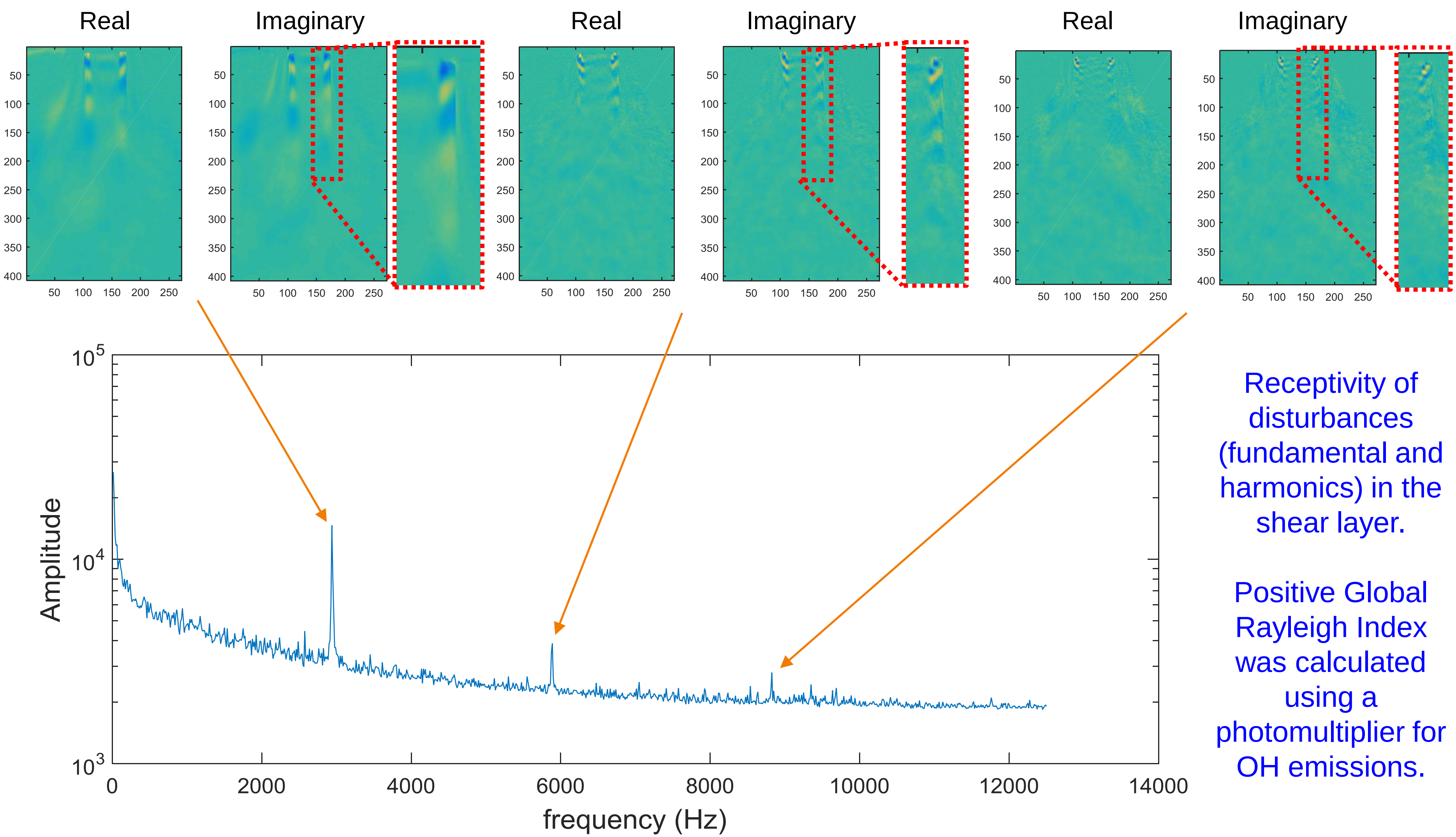
- Isolates response of flow at forcing frequency and harmonics
- Single modes can reconstruct convective processes (POD requires two modes)
- Less efficient at reconstructing signal energy compared to POD

# Max Forcing PAN:  Nonreacting




Receptivity mainly in the fundamental, some coherence at harmonics.

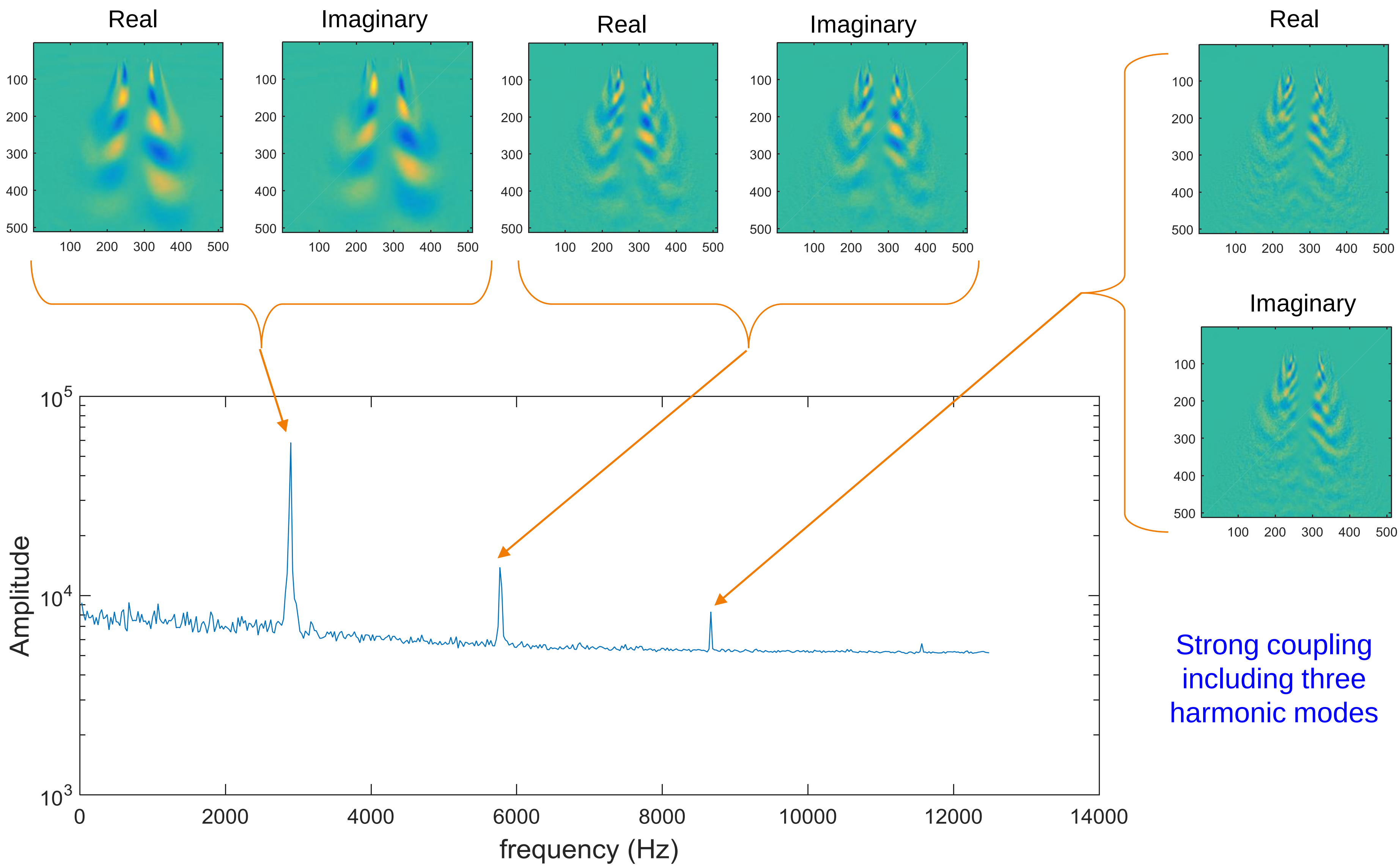
# Max Forcing PAN:  Reacting




Receptivity of disturbances (fundamental and harmonics) in the shear layer.

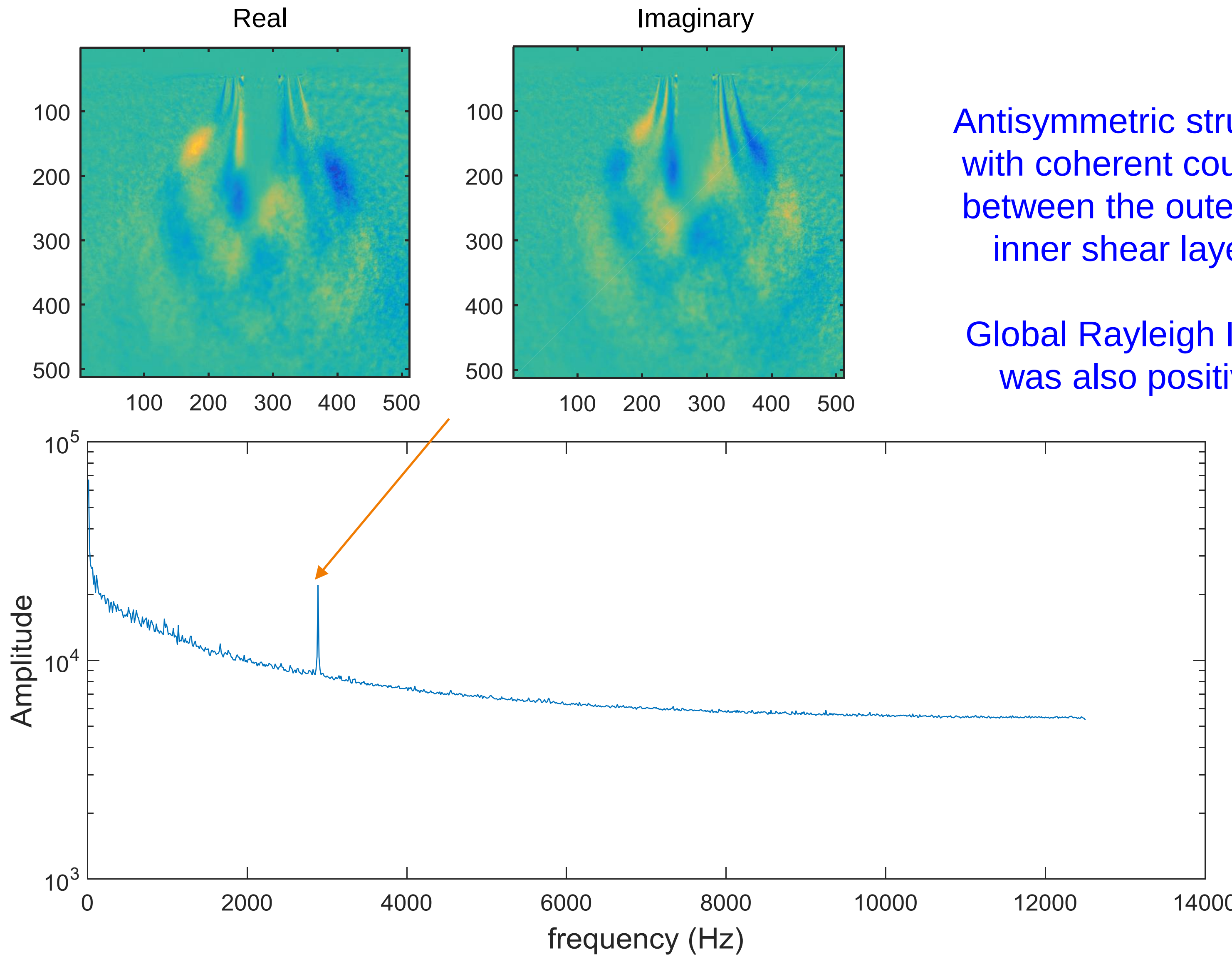
Positive Global Rayleigh Index was calculated using a photomultiplier for OH emissions.

# Max Forcing PN:  Nonreacting




Strong coupling including three harmonic modes

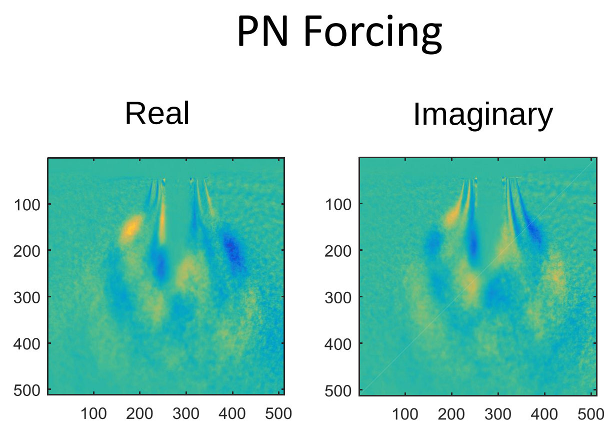
# Max Forcing PN:  Reacting

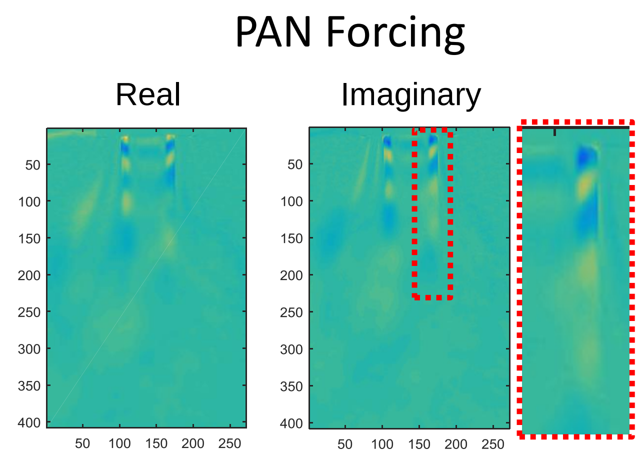



Antisymmetric structure with coherent coupling between the outer and inner shear layers.

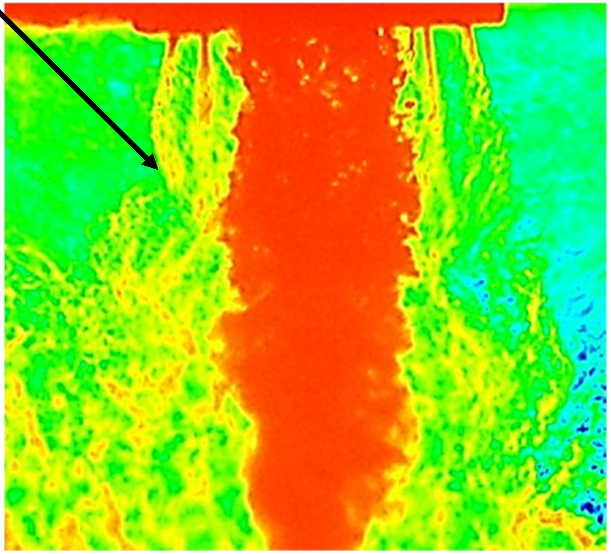
Global Rayleigh Index was also positive.

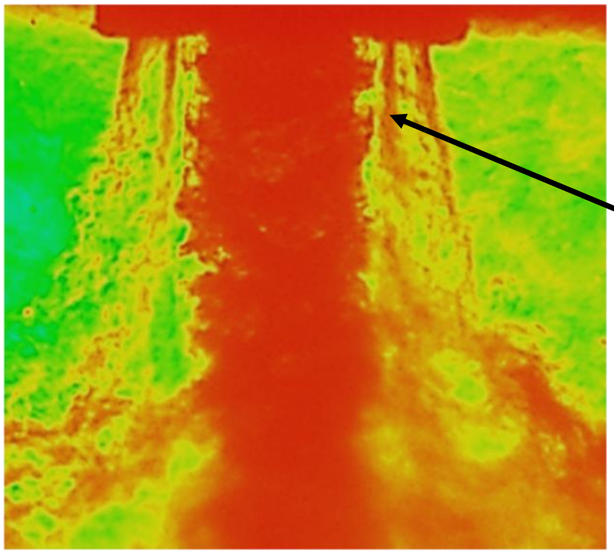
# Max Forcing:  Reacting




Outer GH2 Jet responds to acoustic forcing





LOX Core responds to acoustic forcing

# Conclusions, unforced

- **A blurred interfaced between the GH2 and LOX appears to fibrous atomization regime.**
- **Reactions cause a significantly more expanded plume due to the vaporization and expansion of the LOX.**
- **A LOX recirculation zone was unexpectedly dominant.**
- **Flameholding is established at the lip, consistent with the observations of others.**
- **Unreacting convective structures propagate downstream at relatively constant velocity.**
- **Reacting structures start at slow speed and gradually accelerate with downstream distance, but never reach the velocity of nonreacting structures.**
- **Reactions shift the spectral content to lower frequencies, consistent with trends observed in the linear stability literature.**

# Conclusions, forced

- **Acoustics do not appear to affect the flameholding.**
- **The GH2/LOX interface is not blurred as nonreacting case instead larger ligaments and droplets are observed to shed.**
- **The shed ligaments and droplet shed within 1 LOX diameter get entrained into the LOX post recirculation zone.**
- **Dynamic mode decomposition detects jet response not only at the fundamental frequency but at higher harmonics.**
- **Reactions produce inconsistent trends in the harmonics:**
  - Reactions promote harmonics at a pressure antinode.
  - Reactions damp harmonics at a pressure node.
- **Flame seems to providing a shielding effect on the LOX core.**
- **Cold flow results predict a wide range of responses when conditions are varied over wider ranges.**

# Future Work

- **Mitigation of 13 Hz mode.**
- **Rayleigh index diagrams to indicate whether response is driving or damping.**
- **Variation of parameters over a broader range, guided in part by linear stability theory.**
- **Three-element interactions.**

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